APPARATUS AND METHOD FOR LOCATING NONLINEAR IMPAIRMENTS IN A COMMUNICATION CHANNEL BY USE OF NONLINEAR TIME DOMAIN REFLECTOMETRY

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application, Serial Number 60/424,499, filed Nov. 6, 2002.

[0002] This application contains subject matter that is related to the subject matter of the following copending applications, both of which are incorporated herein by reference: U.S. Patent Application 09/968,063 filed Oct. 1, 2001 for "A Multistage Equalizer that Corrects for Linear and Nonlinear Distortion in a Digitally-Modulated Signal"; and U.S. Provisional Application 60/422,655 filed Oct. 30, 2002 for "A Multistage Nonlinear Echo Canceller for Digital Communication Systems". Related subject matter is also found in U.S. Patent Application 10/456,270 filed June 6, 2003 for "A Multistage Nonlinear Echo Canceller for Digital Communication Systems With or Without Frequency Division Multiplexing", which claims priority to the '655 application.

BACKGROUND OF THE INVENTION

[0003] This invention relates to a data communication channel and in particular to locating and identifying conditions, including nonlinear impairments, affecting the transmission characteristics of the channel. This invention could potentially also relate to any linear medium that supports wave propagation and can contain sites where nonlinear impairments affect transmission.

[0004] The rapid expansion of the Internet has resulted in an increased demand for a global high-speed data network for communication between Internet subscribers and ISPs. In response to the demand, the worldwide telephone network and the cable television network have been adapted to provide this service. While much of the telephone network has been adapted to support advanced digital communications between central offices, the link from a central office to the premises of a local subscriber

is still predominantly the twisted pair copper loop (also called a "subscriber loop"). At present, there are in place many miles of twisted pair copper subscriber loops that were originally designed to carry low frequency analog voltage voice signals. To meet the Internet requirement of transferring packetized digital information, new encoding and modulation methods have evolved to carry higher digital data rate transmissions over these low frequency telephone network loops. For example, Digital Subscriber Line systems (DSL), share in common accepting digital inputs from a subscriber's or an ISP's computer, converting it to a complex analog signal for high speed transmission over the telephone network, and reconverting it to Internet compatible digital information at the receiving site. Successful high-speed transmission of digital information relies on maximum utilization of the capabilities of the transmission channel, and this requires matching the DSL system requirements to the existing telephone channel characteristics.

[0005] Cable television channels have also being adapted for the transmission of data, and may exhibit problems similar to those experienced in data transmission over the telephone network. These transmissions primarily occur on coaxial cables consisting of an inner conducting wire surrounded by a conducting shield.

[0006] The channels used for transmission of DSL signals are conventionally configured, with channel output being a linear function of channel input, so that even if signals are subject to linear distortion they can be recovered using straightforward equalization techniques. However, a channel that is otherwise entirely linear may be subject to nonlinear effects that occur at one or more discrete locations in the channel. For example, a line driver at the channel input may exhibit some nonlinear distortion, an imperfect contact or splice in the channel may have nonlinear characteristics, or a transformer in the channel may exhibit a significant nonlinearity related to magnetic hysteresis and saturation in the core. These nonlinearities give rise to intermodulation components that become dispersed in time as the signals traverse the channel due to the phase shift of the linear portion of the channel. At the receiving end of the channel these components arrive intermixed relative to each other, and cannot be compensated for or corrected by the linear equalizers known in the art.

[0007] Channel equalization for compensation of signal distortion produced both linear and nonlinear impairments is accordingly a priority requirement for efficient, effective DSL operation over a telephone or cable network. U.S. Application 09/968,063 filed Oct. 1, 2001 in the name of Bryant, discloses a method and apparatus for correction of both linear and nonlinear distortion. U.S. Application 60/422,655 filed Oct. 30, 2002 in the name of Bryant discloses a method and apparatus for echo cancellation in lines having nonlinear impairments. Both of these applications are hereby incorporated by reference.

[0008] It is known in the art that time domain reflectometry (TDR) can detect the presence and indicate location of irregularities in a channel by measurement of the return time of pulses reflected from line impairments. However, the method does not distinguish between linear and nonlinear irregularities. U. S. Patent 6,275,050 discloses detection of nonlinear effects caused by corrosion in metal junctions by the measurement of harmonics and intermodulation products generated in signals which have passed through corroded metal junctions.

[0009] Referring to Fig. 1, a TDR readout trace 10, as practiced in prior art, shows a main pulse 12 and noise pulses, e.g. 14, derived from the voltages present on a communication channel having no impairments. The main pulse 12 is connected or coupled to a transmission channel being tested. The channel may include one or more linear or nonlinear impairments which cause reflections of the main pulse 12. These reflections (also "echoes") travel through the channel against the direction in which the pulse 12 travels, arriving back at the point or location at which the pulse was introduced into the channel. For example, in Fig. 2, the main pulse 12' results in a reflection or echo 16 from a linear impairment, and a reflection or echo 18 from a nonlinear impairment, as well as noise signals 14'. (In the drawings, equivalent elements are identified with the same reference numbers, albeit they are distinguished by primes.) It will be noted that the echo 16 from the linear impairment, and the echo 18 from the nonlinear impairment both appear on the trace 10', and are not distinguishable. The traces 10 and 10' display the main pulse, the noise and reflected signals, in a manner known in the art. It will be

noted that, in practice, the echo pulses, e.g. 16, 18 will often be much smaller in height that the main pulse 12'.

[00010] This invention may be embodied in a method or an apparatus for detecting the presence and locations of linear and nonlinear impairments in a transmission channel, and for differentiating the nonlinear impairments from the linear ones. Preferably, the effects produced in echoes from one or more nonlinear impairments are distinguished from and cancel the effects produced in echoes from one or more linear impairments so as to reveal the presence and locations of any nonlinear impairment. I call this invention nonlinear time domain reflectometry (NTDR).

SUMMARY OF THE INVENTION

[00011] A sequence of one or more electromagnetic pulses is applied to the input of a transmission channel in a manner similar to a conventional time domain reflectivity measurement. The pulses are of equal amplitudes and pulse widths, and are generated at a selected repetition rate. The time interval from any one of these pulses to the next is a "sweep". Echoes are produced by reflection of pulses from both linear and nonlinear line impairments, with the echoes occurring in a sweep at times proportional to the impairments' distances from the input point. The pulse repetition rate is chosen to be low enough that all the reflected pulses from a given transmitted pulse will have been received in a sweep before the next pulse is transmitted.

[00012] In accordance with the teachings of the invention, beginning at the time origin, i.e., the rising edge of a transmitted pulse, the voltages on the line are digitized at a sampling rate to capture characteristics of echoes produced in response to the transmitted pulse, and the digital values of the line voltage at each sampling time are stored in individual memory locations. Sampling continues through the entire time interval each sweep between transmitted pulses, and for every transmitted pulse the running average of each set of correspondingly timed digital samples is computed and sequentially stored in memory locations. This leaves the average value of each repetitively received echo unchanged, while the average values of the randomly phased line noise samples tend towards zero, with an attendant increase of signal to noise ratio. This is of particular advantage in that the echo pulses, e.g. 16 and 18 are often much lower in amplitude than the main pulse, 12', as mentioned above. One useful result of a running average is the conservation of memory requirements. But it should also be evident that keeping a running average is equivalent to capturing data continuously for the entire series of transmitted pulses and then performing the averaging process afterwards by dividing this large data set into sections – one section for each transmitted pulse.

[00013] A method enabling the practice of the invention teaches differentiating between a linear impairment and a nonlinear one by recognizing that echoes returned from linear impairments are linearly related to the amplitude of the applied pulse. A

linear impairment presents constant impedance independent of the excitation amplitude or location of the operating point. This constant impedance results in the response being directly proportional to the pulse amplitude. The constant impedance of a linear impairment also causes the response to be independent of the biased location of the operating point along the voltage vs. current characteristic of the impairment, for a constant amplitude pulse. On the other hand, a nonlinear impairment has a nonlinear voltage vs. current characteristic, and accordingly its impedance varies markedly depending upon where the operating point is located. Thus, reflections or echoes from a nonlinear impairment are neither proportional to pulse amplitude, nor, for constant amplitude pulses, independent of the operating point location. By controlling these parameters, and by comparing echoes from two runs for varied parameters, practice of the invention allows distinguishing linear from nonlinear impairments, as will be disclosed in the description of the invention set forth below.

[00014] In one embodiment of the invention, after a first run in which a preset number of transmit pulses cycles are coupled to a transmission channel under test, the amplitudes of the transmitted pulses are increased by a fixed factor, for example, by a factor of 2, and the entire process repeated for a second run. In this second run, identical routines for sampling, and then separately storing the digitized line voltages in a corresponding set of memory locations, are performed. The stored data values from the lower pulse amplitude run are then multiplied by the same fixed factor used to increase the amplitude of the transmitted pulses, and the products are retained, sample by sample, in storage. The two sets of final stored values are then subtracted from each other after the second run's data is multiplied by the fixed factor from the data value in the corresponding memory location of the stored first run's data.

[00015] For a linear line impairment the resultant echo amplitude is linearly related to the amplitude of the incident transmitted pulse, so the data from the lower amplitude run, when multiplied by the fixed factor, will increase by exactly the magnitude of the multiplying factor. Therefore, in the second run a linear impairment echo will scale to the same amplitude as the echo this linear impairment exhibited during the higher pulse amplitude run. On the other hand, the echo from a nonlinear impairment during the

higher pulse amplitude run will not be linearly related to the amplitude of the transmitted pulse. Due to the curvature of the voltage/current characteristic of the nonlinearity, the impedance of the impairment is a nonlinear function of the transmitted pulse amplitude, and the amplitude of echo from the impairment is distorted relative to the transmitted pulse amplitude. Accordingly, the amplitudes of echoes from the same nonlinear impairment do not scale in the ratio of the fixed multiplication factor from the first run to the second.

[00016] Upon subtraction of the data from the two runs, a residual response is produced and the linearly generated echoes will cancel, while an echo from a nonlinear impairment will be apparent as the finite difference between the data values stored in memory. Lack of any effects produced by nonlinear impairments will result in a featureless residual response even during the time when the main pulse is being transmitted. If the residual response departs significantly from zero, it indicates the presence of a nonlinear impairment. The sample number for which a departure first occurs can be used to calculate the distance to the nonlinear impairment. Fig. 3 shows the residual response which corresponds to the conventional TDR result shown in Fig. 2. Note that only the pulse 18' is visible which corresponds to a nonlinear impairment in the line. The transmitted pulse 12 and echo 16 from a linear impairment do not have corresponding features in Fig. 3.

[00017] Fig. 4 illustrates experimental data demonstrating the effectiveness of the invention in detecting a nonlinear impairment. In this figure, the trace 128 shows the residual response for a line having no impairments, the trace 130 shows the result for the same line having a linear impairment located 3000 feet downline, and the trace 132 shows the result for the same line having instead a nonlinear impairment at the same location. Note that the residual pulse can be positive or negative depending on the nature of the nonlinearity at the impairment site.

[00018] In another embodiment of the invention, the transmitted pulse amplitude remains constant but the operating point is displaced by a bias current applied to the impairment by way of the transmission channel under test. Data is acquired from two

runs, the runs differing in that either the bias current is changed or the pulse amplitude polarity is reversed from the first to the second run, so that the operating point and accordingly the impedance from a nonlinear impairment changes, while the impedance of a linear impairment is unchanged. The two data runs are processed as outlined above, so that the averaged linear echoes cancel out, while the nonlinear echoes are displayed. By keeping the pulse amplitude constant this method has the advantage of canceling out any distortion that is inherent in the pulse generation or in the recovery of the echo signal. This embodiment is particularly practical for telephone lines at the customer end where telephone line voltage can be utilized to generate the desired bias current.

[00019] The invention will be described with reference to the below-described drawings, in which:

BRIEF DESCRIPTION OF THE DRAWING

[00020] Fig. 1 is a graph of a time domain reflection display with no line impairments, as known in the art;

[00021] Fig. 2 is a graph of a time domain reflection display with line impairments present, as known in the art,

[00022] Fig. 3 is a graph of a time domain reflection display illustrating operation of the invention,

[00023] Fig. 4 is a plot generated by the invention from experimental data from a twisted pair transmission line for cases in which there is no impairment in the line, there is a linear impairment at 3000 feet in the line, and there is a nonlinear impairment at 3000 feet in the line.

[00024] Fig. 5 is a block diagram of an apparatus according to one embodiment of the invention,

[00025] Figs. 6, 8, and 9 are flow diagrams of steps illustrating practice of another embodiment of the invention,

[00026] Fig. 7 is a voltage versus drawing useful in understanding the embodiments of the invention illustrated in Figs. 5, 6, 8, and 9,

[00027] Fig. 10 is a block diagram of an embodiment of the invention where a bias current is applied to the transmission line and an operating point is changed by reversing pulse polarity,

[00028] Fig. 11 is a drawing useful in understanding the operation of the embodiment illustrated in Fig. 10,

[00029] Figs. 12-14 are flow diagrams illustrating practice of still another embodiment of the invention, and

[00030] Fig. 15 is a block diagram of an embodiment of the invention wherein an operating point is changed by turning a bias current to a transmission line on or off.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[00031] In an embodiment of the invention shown in Fig. 5, a digital computer 20 outputs a pulse of programmable amplitude and repetition rate to a pulse amplifier 22. (The apparatus of the invention may be packaged as a unit to serve as a portable test instrument, 19, or incorporated into the design of a broadband modem). The pulse amplifier 22 drives a communication channel 24 being swept for the presence of impairments. The communication channel 24 typically has a transmission line including two conductors (e.g., a twisted pair for telephone, a coaxial cable for television), and the pulse amplifier 22 applies a voltage pulse between the two conductors. Coincident with the pulse from pulse amplifier 22, a digitizer 26 begins digitizing the voltage present on the channel 24, and the computer 20 stores the digitized value of each sample in digital storage unit 28. On the next pulse from pulse amplifier 22, the sweep is repeated and the new digitized values are similarly stored. Because the digitizing rate is constant, all storage cells with data from correspondingly timed samples of later occurring sweeps are retrievable by addressing the sample number of the data for the sweep.

[00032] Figs. 6, 8, and 9 set forth a method embodiment of the invention which is illustrated by operation of the apparatus shown in Fig. 5. In this regard, the digital computer 20 initiates at 32 a first run of sweeps consisting of N_1 sweeps with pulse amplitude V_1, and at 34 applies the pulses to the channel. Simultaneously with the occurrence of a transmitted pulse, digitizing of the voltage of the channel (at 36) and the storing of the sequentially derived echo data values (at 38) are initiated. These sequences are repeated until a total of N_1 sweeps in a first run is performed, 40, and then sequences of a second run, shown in Fig.8, are started.

[00033] Before describing the further acts of the method, it is advantageous to consider the differences in the impedance presented by a linear impairment and by a nonlinear one as echo amplitude is directly related to line impedance at the impairment. Referring to Fig. 7, the voltage, (V) and current (I) relationships are shown for a linear impairment having a linear V vs. I characteristic curve 42 and a nonlinear impairment having a nonlinear V vs. I characteristic curve 44. The small-signal impedance of either

impairment is directly proportional to the slope of the relevant curve i.e. 42, 44 at a given voltage. For the linear curve 42, with voltage amplitudes V_1' and V_2' applied, the slopes at points 46, 48 are the same, and hence the impedance at 46, 48 are equal. For the nonlinear curve 44, the slopes for applied voltages V_1' and V_2' at points 50, 52 are different. As a result of this variation of the impedance with voltage, the reflection coefficient for pulses traveling through a nonlinear impairment site will depend on the amplitude of the pulses, while in the linear case the reflection coefficient will remain constant for all pulse amplitudes. It will be noted that the preceding discussion has been simplified by excluding the effects of transmission line impedance and attenuation, which would be needed to obtain the relationship between the voltage V' across the impairment and the pulse amplitude V applied to the line. Nevertheless, the simplification does not affect the result relating to the reflection coefficient.

[00034] It will be appreciated that the practice of the invention does not rely on beforehand knowledge of the specific V vs. I characteristics of the nonlinear impairments present in the channel. It is sufficient that the parameters of the channel measurement be controlled and configured such that reflections from a nonlinear impairment occur at different impedances during the different runs of a test. This configuring may be accomplished by varying pulse amplitudes or by various biasing techniques, so that different, selectable portions of the nonlinear V vs. I characteristic are addressable during a run.

[00035] Referring to Fig. 8, a second run of N_2 sweeps is initiated (at 54) with a pulse amplitude V_2 greater than V_1. Transmitting a pulse down the line at 56, starting digitizing the line voltage at 58, storing the samples at 60, and stopping the run after N_2 sweeps at 62, repeats the sequences of the first run with the greater pulse amplitude, V_2. At the conclusion of the run, the acts of Fig. 9 are initiated.

[00036] Referring to Fig. 9, the average of the cell data for each corresponding sequential sample of the first run is calculate at 64, by the digital computer 20. Similarly, the average of the cell data for each corresponding sequential sample of the second run is calculated at 66. (It will be appreciated that the above sequences have been set forth for

convenience of exposition. In an actual program it may be easier to first accumulate all the data, and then to implement the averaging processes.) The ratio, R, of the amplitudes of V_2 / V_1 is also computed at 68, and each of the average values of the cells of the first run are multiplied by R at 70. The averages of the first run, after multiplication by R, are subtracted cell by cell, from the corresponding averages of the second run. The differences are sequentially examined for evidence of a residual pulse indicating the presence of one or more impairments in the line. Examination may be visual or may employ a numerical algorithm.

[00037] With reference again to Fig. 3, it will be seen that there no echo signal from the linear impairment 16 appears, while an echo signal from the nonlinear impairment 18 is displayed. As described above for a linear impairment, the amplitudes of the echoes from pulses of different amplitudes will be directly proportional to the pulse amplitudes. Hence, the average of the echo amplitudes from linear impairment 16 for applied pulse V_1 when multiplied by the ratio of V_2 / V_1, will equal the average echo amplitudes for applied pulses V_2, and the differences between the averages of the first run and the second run will be zero. The same linear analysis applies to the main pulse feed through 12, 12′, and these signals do not appear in the display of Fig. 3. However, for a nonlinear impairment, different impedances result from application of voltage pulses of different amplitudes (Fig. 7) and accordingly the amplitudes of echoes for the different pulse amplitudes are not linearly related. After multiplication of the data acquired for the first run by the ratio of V_2/V_1, the echo amplitude averages from the first and second runs are not equal, and their differences do not cancel. Hence, a resultant signal is displayed only at the sample positions of nonlinear impairments. It is to be noted that the residual pulse 18' is likely to be smaller in amplitude than 18 of Fig. 2, and could be positive going or negative going depending on the nature of the nonlinearity.

[00038] Once a residual pulse has been identified, the location of the corresponding nonlinear line impairment may be determined. Referring the results displayed in Fig. 4, a residual pulse is apparent in the third trace 132. Estimating the onset of this pulse as occurring at sample 27, for a sample rate of 2.5 million samples per second, the onset occurred at about 10.8 microseconds. Taking the pulse velocity in the line as about 0.6

times the speed of light or about 589 feet per microsecond, we can calculate the round trip distance traveled by the pulse as 589 times 10.8 which equals 6368 feet. This corresponds to a one way distance of 3182 feet, which is in reasonable agreement with the known distance to the nonlinear impairment of 3000 feet. Knowing the distance to the impairment and the amplitude of the residual pulse and the attenuation coefficient for the line should be sufficient information to roughly characterize the severity of the impairment. If more detailed information is desired, the NTDR testing can be repeated at several different pulse amplitudes to further characterize the nonlinear impairment.

[00039] With reference again to Fig. 3, it is to be noted that the noise floor 14″ is of lower amplitude than the noise floors seen in Figs. 1 and 2. The noise 14″ is derived by averaging the sampled noise measured during the digitizing processes, and because the noise is a random signal the average value when no echo is present tends to zero out.

[00040] In another embodiment of the invention, shown in Fig. 10, the location of the channel operating point is varied between the two data runs through the use of a bias current. In the transmission lines of a plain old telephone system (POTS) current can be conveniently obtained by using the power supplied to the line by the telephone company. However the current could also be supplied by other means if necessary. As a first example of this embodiment, a test apparatus indicated by reference number 19' comprises the same components as the apparatus 19 of Fig. 5, with the two wire outputs 76, 78 from a pulse amplifier 22' explicitly shown. A reversing switch 80 is connected between the pulse amplifier 72' and an active POTS telephone line 82 under test. The digitizer 24' is connected to one side of the telephone line 82. The telephone company central office 84 applies a dc voltage between the two conductors of the telephone line 82, and this voltage can be used to generate a bias current in the line. A resistor 86 or other conducting element at the test apparatus 19' is placed across the line 82 during the test to provide a current path, thereby generating the bias across the line impairments. Fig.11 shows the V vs. I characteristics for linear and nonlinear impairments with bias. The resulting dc bias voltage V_4 shifts the quiescent operating points, (i.e. the points about which the pulse signals are applied), of a linear impairment to point 90 and to point 88 for a nonlinear impairment. The impedances for positive applied equal amplitude

pulses are the slopes of the V vs. I characteristics at 92 for linear impairments, and at 96 for a nonlinear one. The impedances for negative applied equal amplitude pulses are the slopes at 94 f or linear impairments and 98 for nonlinear ones. As before, the lack of any change in impedance for the linear case means that there will be no change in the reflection coefficient, while the changing impedance in the nonlinear case will typically result in a change in the reflection coefficient.

[00041] A third run (so identified to differentiate it from the first and second runs of the previously disclosed embodiment), is performed with the switch 80 in the position shown in Fig. 10, and includes the acts of Figs. 12-14. The third run is initiated at 100 with positive pulses having a magnitude $+V_3$ applied to biased line 82. These pulses are transmitted 102 down the line, the line voltages are digitized 104, and the sample values stored 106 in run 3 storage. The number of sweeps performed is tested at 108, and the method continues until a preset number N_3 of sweeps occurs at 108. When N_3 sweeps are finished the reversal switch 80 is operated, and its transfer contacts reverse the polarity, of the pulse applied to the line 82 from $+V_3$ to $-V_3$ without changing the absolute amplitude of the pulse. A fourth run is initiated at 110 with pulses transmitted down the line 112, the line voltage is digitized at 114, sample values stored at 116, and a test is performed at 118 to determine if the fourth run is completed. Upon completion, averages are computed for cell values of the third and fourth runs at 120 and 122, the average values for the third and fourth runs are subtracted at 124 on a cell by cell basis, and the differences examined as a function of sample number to show the nonlinear impairments, as illustrated in Fig. 3.

[00042] It will be noted that additional versions of the embodiment of Figs. 12-14 are possible in the practice of the invention. Pulses of equal amplitudes and the same polarity may be used, and it will be appreciated that the combination of equal amplitude, same polarity pulses functions equally well as long as the nonlinear impedances result in pulse echoes from the two runs that are distinguishable from the echoes reflected from the linear impairments. This may be accomplished by making a first reflectometry measurement without any bias current in the line, and then making a second measurement

with the line biased. Fig. 15 illustrates an example, wherein for both runs the pulse amplitude and polarity remain the same.

[00043] In Fig. 15, still another embodiment of the invention is shown. In Fig. 15, the test apparatus denoted by reference number 19" comprises the same components as the test apparatus 19 of Fig. 5, albeit for clarity only the pulse amplifier 22" and digitizer 24" are shown. The bias current is activated by the closure of switch 85' connected to a low pass filter 83. This filter will allow the passage of the dc bias current, but will block the passage of pulses, thus preventing any change in the loading of the pulses when the switch 85' is closed. In some cases the load resistor 86' may be replaced by a short circuit to maximize the bias current. The low pass filter 83 may be implemented as a series inductor. When the switch 85' is closed, the resultant current biases the impairments as previously described, and a reflectometry run generates data resulting from the biased values of the impairment impedances in the line. With the switch 85' open, a second run provides different echo responses from the nonlinear impairments, since the nonlinearities' impedances depend on the bias point, while the impedances, and correspondingly the echoes, exhibited by the linear impairments are unchanged. The data from the runs are processed as previously described, and the nonlinearities are displayed and identified.

[00044] The invention has been described in detail with particular reference to a number of embodiments thereof, but it will be appreciated that variations and modifications can be effected within the spirit and scope of the invention. It may also be that the invention has application to other fields besides that of the communications channels discussed in detail above.

I CLAIM: